AROUND THE KNEE: SIMULTANEOUS SURFACE AND UNDERGROUND MEASUREMENTS AT BAKSAN.

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ABSTRACT

We present the experimental data on the knee, as observed in the electromagnetic and high energy muon ($E\mu \geq 230$ Gev) components.

INTRODUCTION.

The break in the shower size spectrum (the so called "knee") at about 10^6 particles was observed first by the MSU group more than 40 years ago. But the nature of the knee is the puzzle up to date. The astrophysical interpretation is the most natural. It is the steepening of the primary cosmic ray spectrum at energy $\approx 2 \times 10^{15}$ eV. Reasons for such steepening can be found in acceleration processes as well as in propagation processes. For example, there is an energy limitation of the acceleration at the shock front in SNRs. And also, the containment of cosmic rays in galaxy due to magnetic fields is decreasing with encreasing particles energy. These processes are leading to more heave primary composition after the knee. The knee also can be a result of the nuclear fragmentation in the acceleration region. It is leading to the lighter composition after the knee. Alternative interpretation is a change in the hadronic interaction properties.

The situation around the knee is very complicated now. And solving of the problem requires accurate measurements of the different EAS component both to verify the main features of the hadronic physics, and to measure the variations with energy of the primary spectrum and composition.

THE APPARATUS.

The electromagnetic component in our experiments is measured by the "Andyrchy" EAS array [1, 2]; high energy muon ($E\mu \geq 230$ Gev) component is measured by the Baksan Underground Scintillation Telescope (BUST) [3]. The location of the "Andyrchy" straight above the BUST gives us a possibility for simultaneous measurements of both components.

The EAS array "Andyrchy" consists of 37 plastic scintillation detectors with an enclosed area of $4.5 \cdot 10^4 m^2$. Each scintillator has an area of $1 m^2$, with thickness of 5cm and is viewed by one PMT. The distance between detectors horizontally (projection) is about 40m, the maximum vertical distance (projection) is about 150m (Fig.1). The central detector is located above the telescope and the corresponding vertical distance is 360 m. The altitude above sea level is 2060 m (atmospheric depth $800 gr/cm^2$). Each detector is equipped by active thermoregulation. The temperature is within 1°C at the PMT (and electronics block)

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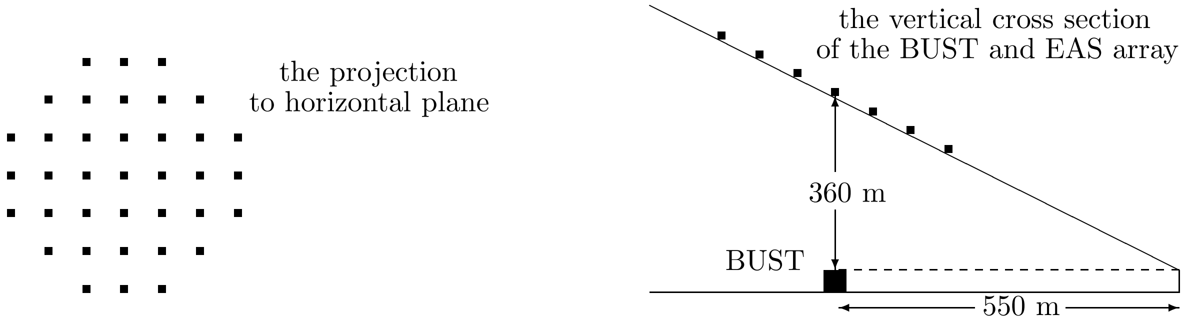

Fig.1. The EAS array "Andyrchy".

and within 3°C at the scintillator [2].
The electronics inside each detector consists of:
a) DC converter (27 V - 2 kV) and voltage divider for PMT high voltage supply;
b) a suppressor of the afterpulses;
c) an amplifier of the anode signal of the PMT;
d) a logarithmic Charge-to-Time Converter (CTC) of the PMT signals.
The output CTC signal has a duration proportional to logarithm of the charge at 12th dynode [4]; its leading edge is formed using an anode signal and is used for timing measurements [5].

The energy deposition measurements is performed in natural units - it is so called relativistic particles. One relativistic particle (r.p.) is most probable energy deposition from single cosmic ray particle. For our detector it is 10.5 Mev. The range of the energy deposition measurements is from 0.5 r.p. (the threshold of the CTC) up to more than 1000 r.p. Figure 2 shows a percent error in the energy deposition measurements in the detector. It is an experimental result, including all apparatus errors as well as showers fluctuations.

Trigger formation and all measurements are performed in a registration room, which is placed near a center of the array (length of connection cables up to 280 m). The shower trigger is produced when 4 or more detectors are fired ($\Delta t = 3.2\ \mu s$). The trigger rate is $8.8 s^{-1}$.

The BUST is a large underground installation with dimensions $16m \times 16m \times 11m$ [3]. The BUST consists of 3150 liquid scintillation detectors. Each detector has dimensions $0.7m \times 0.7m \times 0.3m$. The coincidence trigger is produced when one or more muons crossing the telescope ($\approx 12 s^{-1}$) coincide with shower trigger; the coincidence rate is $0.1 s^{-1}$. For used selection conditions (near vertical events) the threshold energy of muons is 230 Gev.

THE EAS SIZE SPECTRUM.

In this analysis we used the following EAS selection conditions:
1) near vertical events (with zenith angles $\theta \leq 10°$, the mean atmospheric depth is 805 gr/cm^2).
2) only the showers with axis inside of central part of array (the distance from the central detector not more than 70 m) were included in analysis.

EAS arrival directions are obtained from the times of flights among the different detectors. For used events the angular resolution is 1.9°. The reconstruction of shower parameters is performed in units of relativistic particles. The shower size $N_{r.p.}$, the slope of the lateral distribution function and the core location are determined by a χ^2 method, in which the logarithm of the energy deposition in each detector is compared with the one expected from the NKG lateral distribution function

$$\rho(r) = N_{r.p.}\frac{C(s)}{r_0^2}\left(\frac{r}{r_0}\right)^{(s-2)}\left(1+\frac{r}{r_0}\right)^{(s-4.5)}$$

with $r_0 = 96m$. The NKG function reproduce with a good accuracy the experimental data [6]. The accuracy of reconstruction is calculated by analysing data obtained from a simulation that includes the experimental dispersion. Figure 3 shows a percent error in the size determination versus the size. Figure 4 shows the differential size spectrum in r.p. units for $7 \cdot 10^5 \leq N_{r.p.} \leq 2 \cdot 10^7$., where the shower parameters and size spectrum are reconstructed without distortions. The effective running time is $5.02 \cdot 10^7$ s (580.9 days). The steepening of the spectrum is observed at $N_{r.p.} \approx 2 \cdot 10^6$.

The standart definition of the shower size N_e is the total number of the charged particles (mainly $e^{\pm}$) at the level of observations. The measured size $N_{r.p.}$ is the total energy deposition in infinite detector. The relations between $N_{r.p}$ and N_e for different primaries (protons, irons and gammas) was obtained by means of a simulation of the shower particles crossing the detectors and their housing for vertical direction. The input data for this simulation are taken from the CORSIKA 4.50 EAS simulation, the threshold $e^{\pm}$ energy is 5 MeV. Figure 5 shows the differential size spectra after conversion from $N_{r.p.}$ to N_e by assumption different primaries (gammas, protons and irons from top to down). One can see that the conversion from the total energy deposition $N_{r.p.}$ to the number of charged particles N_e is sufficiently ambiguous procedure.

THE $\overline{N}\mu(N_{r.p.})$ DEPENDENCE.

The underground telescope records only a part from the total number of shower muons, therefore for $\overline{N}_\mu$ determination the method of the mean shower have been used [7, 8]. Events for fixed $N_{r.p.}$ are binned in 10 distance intervals with $\Delta R = 10$ m (R is the distance between shower's core and underground telescope). For each interval the number of muons in the telescope is:

$$M(R_i, N_{r.p}) = \sum_{j=1}^{K} m_j$$

(i=1,2,..10), where $K = K(R_i, N_{r.p})$ is the number of showers and m_j is the number of muons in the telescope for j-th shower. To explain it more clear - the number of muons in the telescope for concrete shower can be from 0 up to ≈ 150. Therefore,

$$\overline{n}(R_i, N_{r.p}) = M(R_i, N_{r.p})/K(R_i, N_{r.p})$$

is the mean number of muons for showers with size $N_{r.p}$ and distance R_i. The mean number of muons for showers with size $N_{r.p}$ is:

$$\overline{N}_\mu(N_{r.p}) = (1/S_t)\sum_i \overline{n}(R_i, N_{r.p}) \cdot S_r(R_i)$$

where S_t is the effective telescope area (200 m^2) and $S_r(R_i)$ is ring area.
Fig.6 shows the dependence of the mean number of muons in the shower $\overline{N}\mu$ on $N_{r.p.}$ for $7 \cdot 10^5 \leq N_{r.p.} \leq 2 \cdot 10^7$, the effective running time is $4.28 \cdot 10^7$ s (495.1 days). One can see some breakdown of single power law $\overline{N}\mu \sim N^{\alpha}{}_{r.p.}$ close to the knee ($N_{r.p.} \approx 2 \cdot 10^6$).

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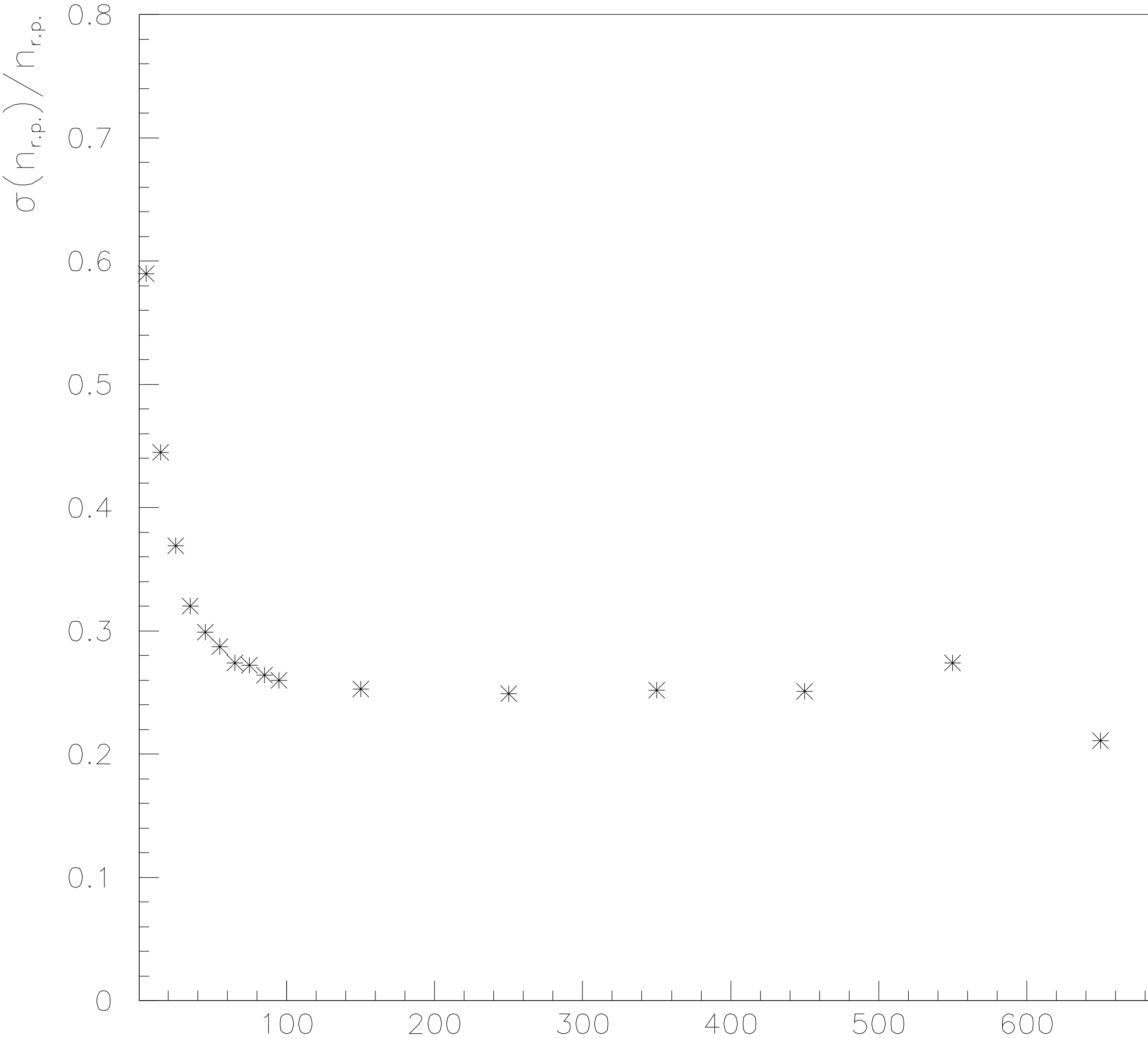

Fig.2. Fluctuations of the energy deposition in the de

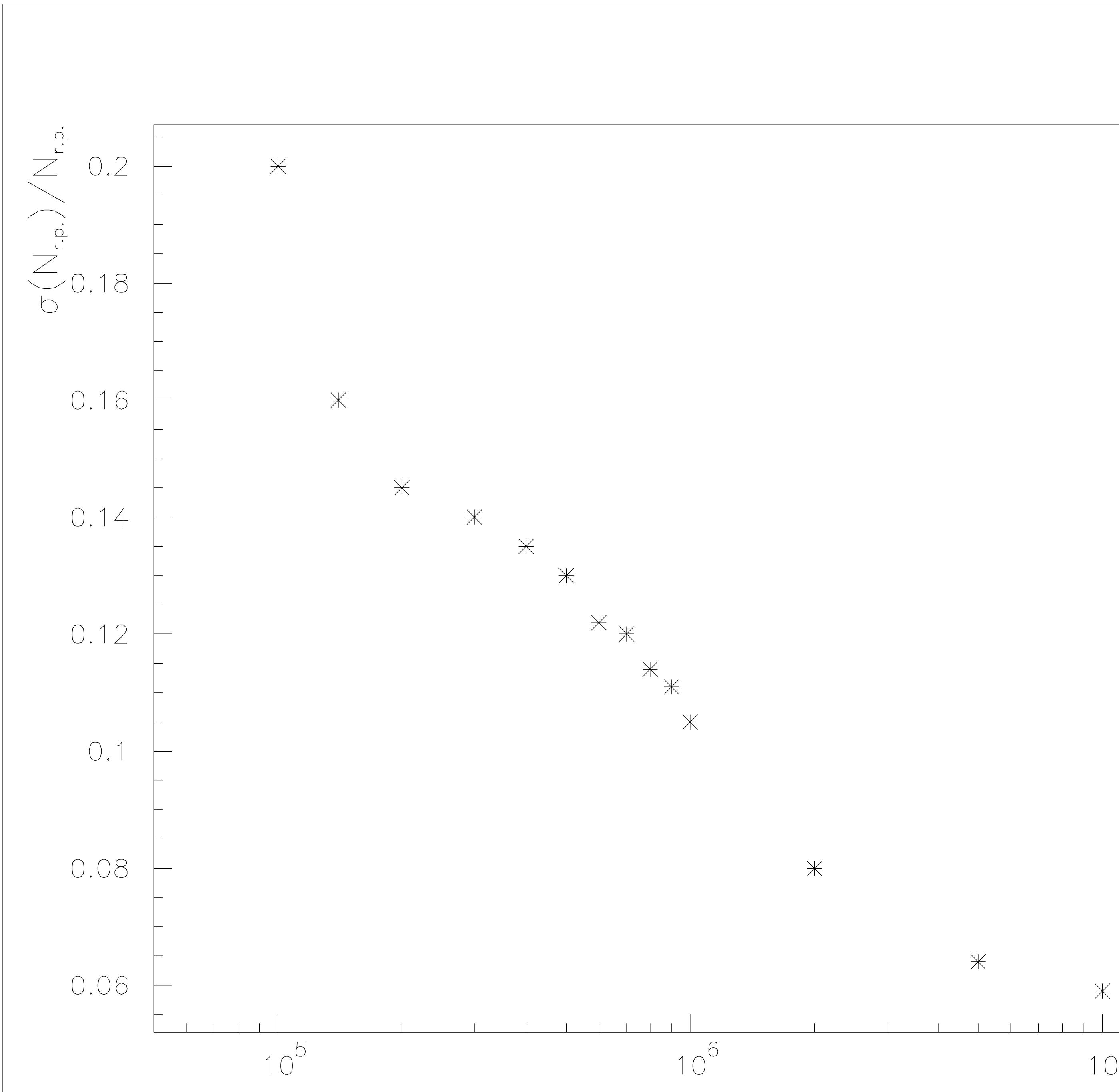

Fig.3. Percent error in size determination versus

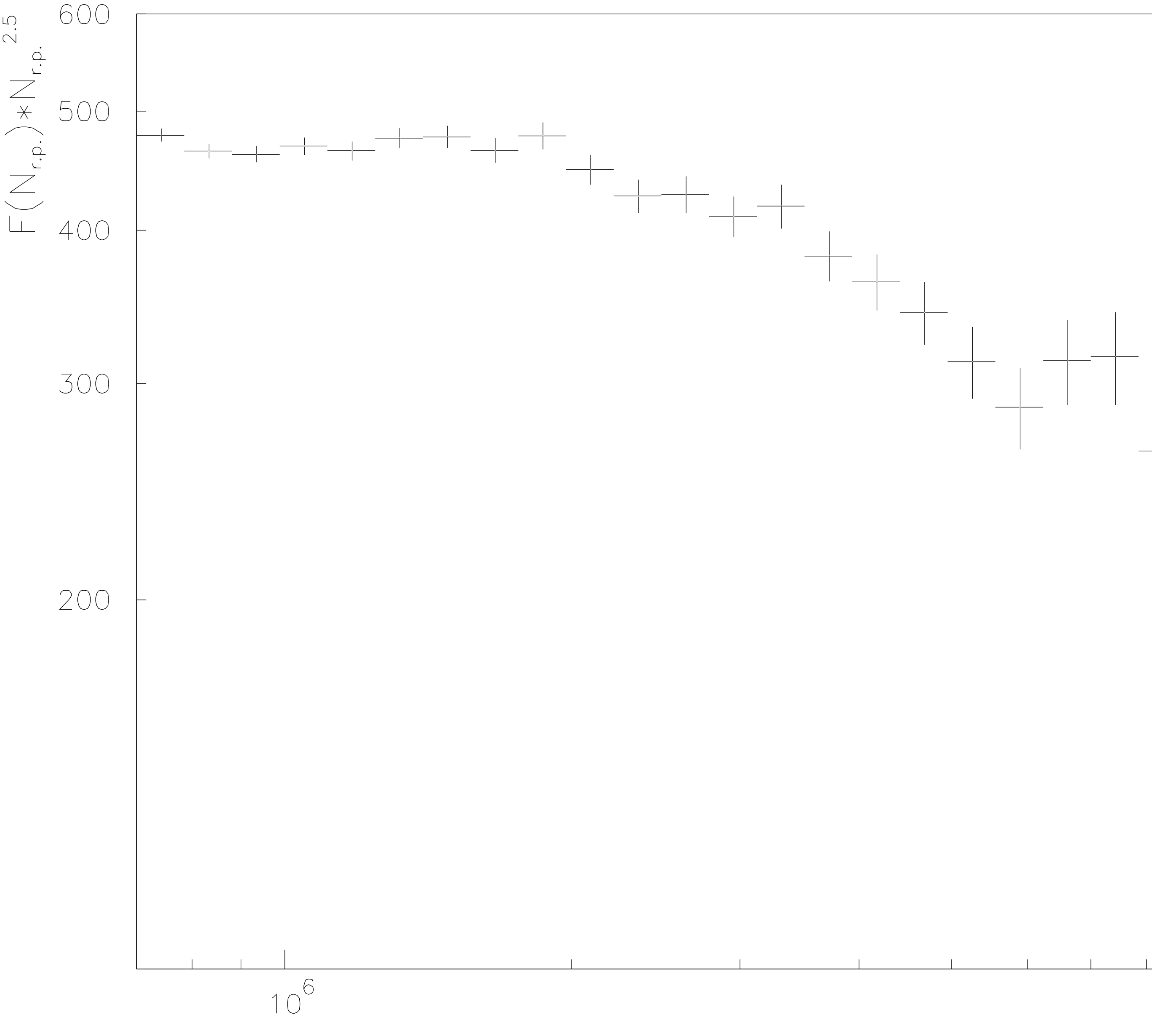

Fig.4. EAS differential size spectrum (in r.p. units

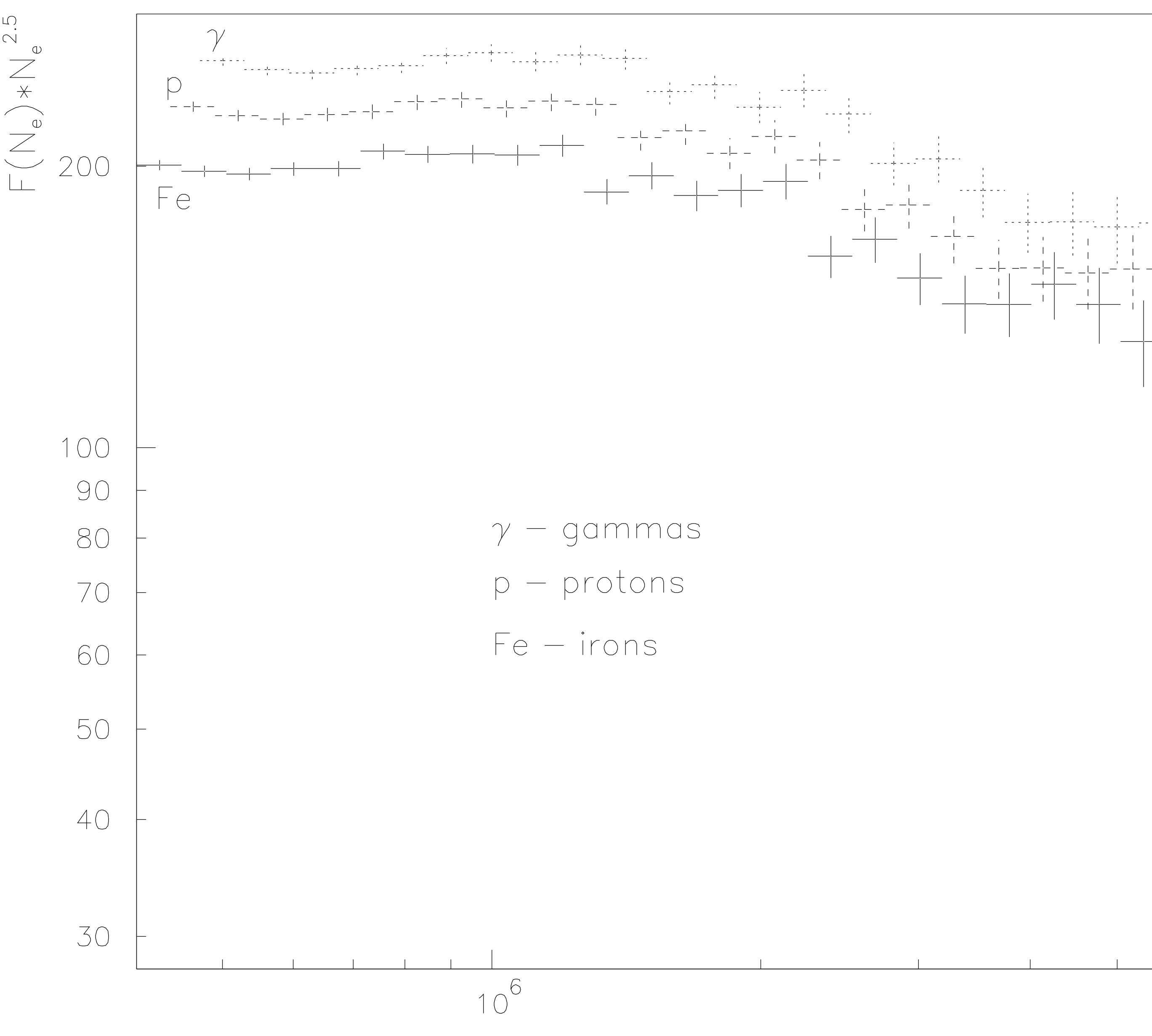

Fig.5. EAS differential size spectrum for different prir

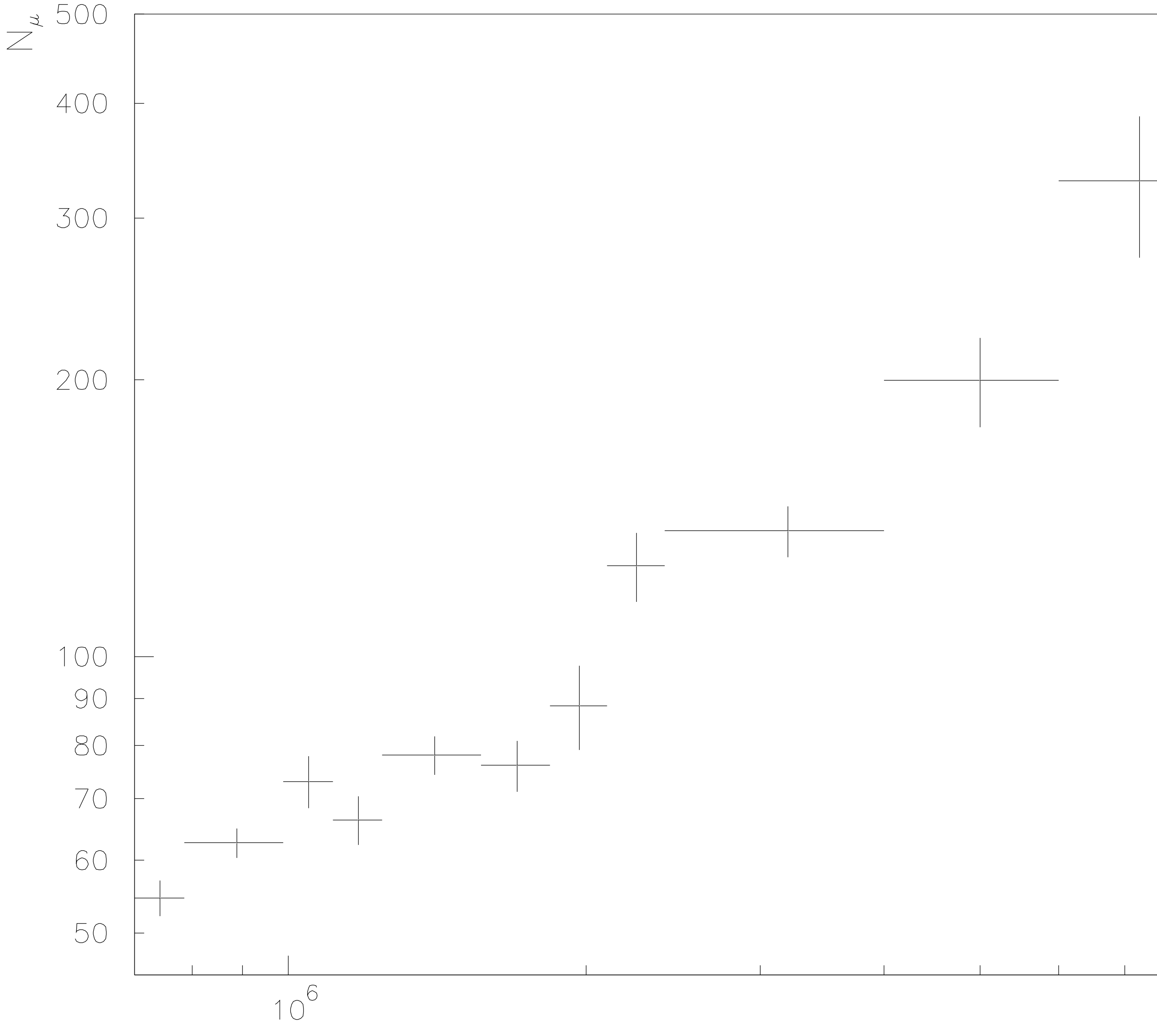

Fig.6. $N_\mu(N_{r.p})$ dependence.